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THE STRENGTH AND PLASTICITY OF ANISOTROPIC METALS

Technical Report WAL TR 834.12/2-2

by

W. A. Backofen

and

W. F. Hosford, Jr.

31 March 1963

Third Quarterly Report

Contract DA-19-020-ORD-5719
Boston Procurement District

Ordnance Management Structure Code 5010.11.8430051
Department of the Army Project 59332008
U. S. Army Materials Research Agency
Watertown 72, Massachusetts

Cambridge, Massachusetts

AD NO.____________

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Plasticity
Stress and strain

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Abstract

Rolling and transverse-direction tensile tests have been made on specimens from a series of magnesium-alloy sheets. The dependence of strain ratio on alloy and testing direction is rationalized in terms of the (0001) spread of the pole figures. It is suggested that the increase of strain ratio with strain and with annealing may result from the behavior of localized shear bands.

Introduction

Work in the past quarter has been centered around the plastic anisotropy of several magnesium-alloy sheets. Tensile tests have been made on flat specimens cut in the rolling and transverse direction from 1/8" or 5/32" sheets of AZ31B, HK31A, and ZE10A alloys in both as-rolled and annealed conditions.

TABLE I

MAGNESIUM ALLOY SHEETS

Alloy	Treatment	Thickness (in.)
AZ31B-H24	Commercial Temper	.125
AZ31B-0	Commercial Anneal	.125
HK31A-H24	Commercial Temper	.160
HK31A-H24	Annealed 1 hr. at 700°F	.160
HK31A-H24	Annealed 1 hr. at 950°F	.160
ZE10A-H24	Commercial Temper	.125
ZE10A-H24	Annealed 3 hrs. at 500°	.125

Experimental Procedures

Specimens were machined with a six-inch reduced section of one-half inch width. A constant drive rate of .02"/minute was used throughout, except in one test in which the rate was increased to 2"/minute. During testing the specimens were periodically unloaded and removed from the machine to facilitate strain determinations. Vernier caliper measurements between three separate pairs of gage marks were used to obtain an average length strain, $\epsilon_L = \ln L/L_o$. Width and thickness strains, $\epsilon_w = \ln w/w_o$ and $\epsilon_t = \ln t/t_o$, were calculated from micrometer measurements at three places. Thickness strains based on the constant volume relationship, $\epsilon_L + \epsilon_w + \epsilon_t = 0$, agreed closely with those obtained directly from the thickness measurements; the latter a[illegible]sed througout this report.

Results

Generally the R value for characterizing plastic anisotropy is calculated with the total strains, $R = \epsilon_w/\epsilon_t$, at a particular stage of extension. If R is constant, the method is sound.

In these materials, however, the measured values of R increased continuously during the tests. When R is variable, the plastic anisotropy at any stage of straining ought then to be identified by an instantaneous value, $R_i = d\epsilon_w/d\epsilon_t$ based on the strain increments during a small amount of pulling. It should be noted that R_i will change more rapidly with strain than the usual strain ratio because the latter is dependent upon values of R_i over the whole history of straining.

Values of R_i were calculated from successive strain measurements and are shown as functions of length strain in Figures 1-3. Figures 4-6 give the corresponding engineering stress-strain curves.

General conclusions may be drawn from the data:

1. The instantaneous strain ratio R_i which is initially low (usually less than unity) increased rapidly with strain, the most rapid increase occurring in the first 1 or 2% of strain.

2. R_i values are consistently higher along the transverse direction than the rolling direction.

3. R_i values are always higher in the annealed than in the as-rolled sheets.

4. Largest strain ratios are found in the AZ31B alloy; the least values appear in the ZE10A alloy.

5. Increasing the strain rate by a factor of 100 has no significant aspect on R_i in the ZE10A H-24 sheet. The stress strain curve is raised about 6% by the rate-increase however.

6. Except for the ZE10A alloy, transverse-direction stress-strain curves are higher than the rolling-direction curves. Generally the transverse direction specimens also undergo a greater elongation before failure.

Discussion

It is interesting to compare these observations with the sharpness of the (0001) texture as determined from (0001) pole figures supplied with the sheets by the Dow Metal Products Co. Of particular importance is the amount of spread of (0001) around the rolling plane normal. Figures 5 and 6 are profiles of the pole figures representing the variation of (0001) intensity from the rolling plane normal towards the rolling and transverse for test directions. The variations of R_i from alloy to alloy and with direction of testing correlate qualitatively with these data: the level of R_i is inversely related to the amount of spreading. This correlation can be explained by the fact that stress for slip on (0001) basal planes is much lower than that for slip on $\{10\bar{1}1\}$ pyramidal or $\{10\bar{1}0\}$ prism planes. With enough rotation of the (0001) poles toward the stress axis, basal slip can act to produce sheet thinning and low R_i values. On the other hand, when (0001) spread is small, the shear stress on the basal planes is relatively low and the applied tensile stress can be increased sufficiently for activating $\{10\bar{1}0\}$ prism planes which are oriented so as to cause large width strains (high R values). The smaller amounts of spreading of (0001) in the transverse direction compared to the rolling direction can thus explain the higher R values and flow stresses found in tests along these directions.

The general increase of R_i on annealing and the rapid increase of R_i with strain cannot be so easily rationalized, however. The effect of annealing on the pole figures is small, increasing or decreasing the (0001) spread only slightly. As one possibility, the annealing effect might be related to microstructural features produced by rolling.

Couling, Pashak and Starkey[1] showed that in EK00 and H0 magnesium alloys, thin bands of material are formed across the sheet at an angle to the surface during passage through the roll gap. Apparently, basal-plane alignment in the bands is parallel to the boundaries of the bands. A double-twinning process has been suggested as basic to the local reorientations that are involved. Deformation subsequent to their formation is localized in these bands. The rolling-direction tensile strength is lowered by the band formation but may be restored or increased by annealing. No tensile strain-ratio data were reported in that work. Nevertheless, it could be expected that highly local flow in the bands during extension would cause low R values. Perhaps similar shear bands in materials of the current study will eventually be found to play a role in explaining these observations of the initially low R values, R increasing with straining, and annealing acting to increase R. It can also be imagined that the bands may be responsible for some of the difference observed in rolling-direction and transverse-direction tests.

Certain cracking observations were also made during the course of tension testing. Cracks were often found in or near the neck, on either the face or edge of the specimen. The location (face vs. edge) of the cracks correlated with the strain ratios; face cracks predominated in materials where $R < 1$ and edge cracks where $R > 1$. The trend was particularly clear in AZ31B sheets, probably because of the large difference in R values in the rolling and transverse directions. These observations suggested a series of tests to study the relative effects of edge and face notches on rolling and transverse direction specimens of AZ31B-H24. The results (Table II) are

in accord with predictions made earlier[2] that in specimens with high R values, face notches should impose more severe constraints than edge notches. while the converse should be true if R is less than one.

TABLE II

CRACK LOCATION AND EFFECT OF NOTCH ORIENTATION IN AZ31B-H24

	Unnotched Bars			Face Notched	Edge Notched
Test direction	R_i at $\epsilon_L = .02$	location of cracks	UTS	UTS	UTS
Rolling direction	0.75	face	38,400	40,600	41,700
Transverse direction	2.65	edge	40,600	47,500	45,300

Future Work

Future plans include tests to evaluate the temperature dependence of strain ratios. Since the observed strain ratio seems to depend upon a competition among several deformation mechanisms, and since the relative ease of operation of these mechanisms is affected differently by temperature changes, the strain ratios are expected to depend on testing temperature. Investigation of localized shear bands will be made metallographically and by applying a commercial strain-sensitive lacquer. In an additional phase of the program, magnesium single crystals are currently being tested in plane strain compressions. By controlling the orientation of both compression and elongation directions, different slip and twinning mechanisms can be studied. The results will be reported at a later date.

Summary

Rolling and transverse direction tests on several magnesium alloy sheets revealed that the strain ratio (1) is initially low but increases rapidly with tensile strain, (2) is higher for annealed sheets than for as-rolled sheets, (3) is higher in the transverse direction than in the rolling direction, and (4) varies considerably from alloy to alloy. The latter two observations are consistent with the (0001) pole figures, the strain ratio decreasing as the spread from an ideal (0001) texture increases. It is suggested that the first two observations may be related to the formation of localized bands during rolling. Also the orientation of cracking and notch sensitivity have been related to the observed strain ratios.

References

1. S. L. Couling, J. F. Pashak, and L. Sturkey, "Unique Deformation and Aging Characteristics of Certain Magnesium-Base Alloys", American Society for Metals Transactions, 51 (1959) p. 94.

2. W. A. Backofen and W. F. Hosford, Jr., "The Strength and Plasticity of Anisotropic Metals, First Quarterly Report", 30 September 1962, Technical Report WAL TR 834.12/2.

Acknowledgments

The Dow Metal Products Company kindly supplied the magnesium alloy sheets together with (0001) pole figures.

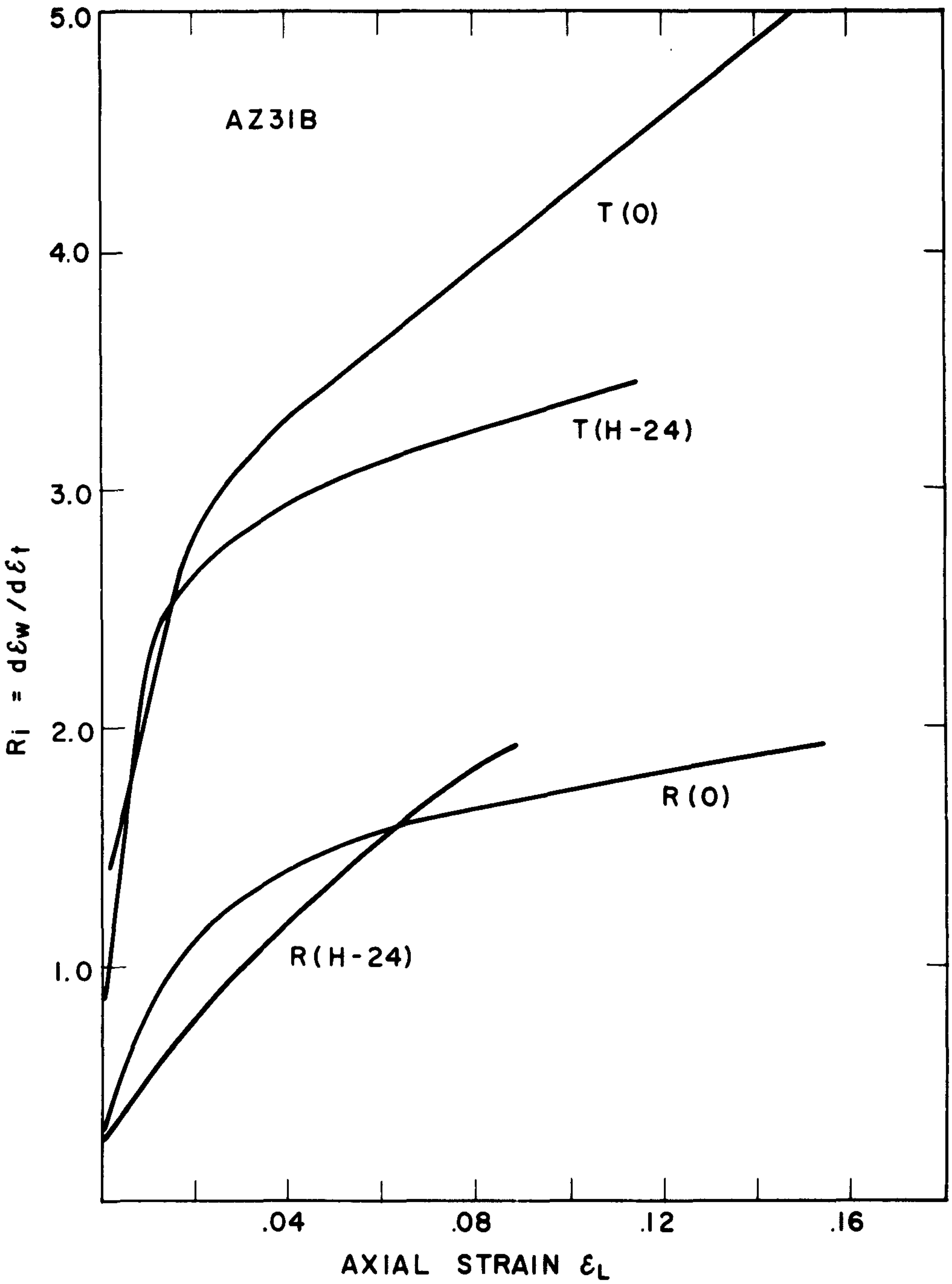

Figure 1. Variation of instantaneous strain ratio, $R_i = d\epsilon_w/d\epsilon_t$ with tensile strain, ϵ_L, for magnesium alloy AZ31B in the H-24 and 0 conditions. R and T indicate rolling and transverse direction tensile tests respectively.

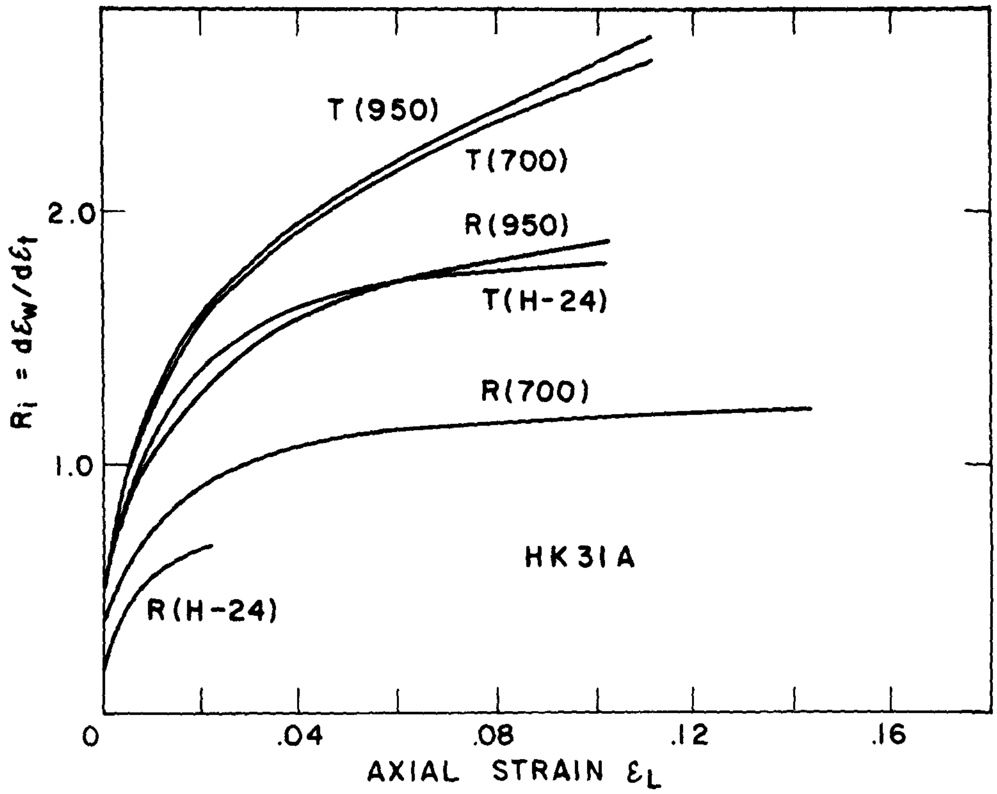

Figure 2. Variation of instantaneous strain ratio, $R_i = d\epsilon_w/d\epsilon_t$ with tensile strain, ϵ_L, for HK31A for magnesium alloy HK31A in the H-24 condition and after one-hour anneals at 700°F and 950°F. R and T indicate rolling and transverse direction tests respectively.

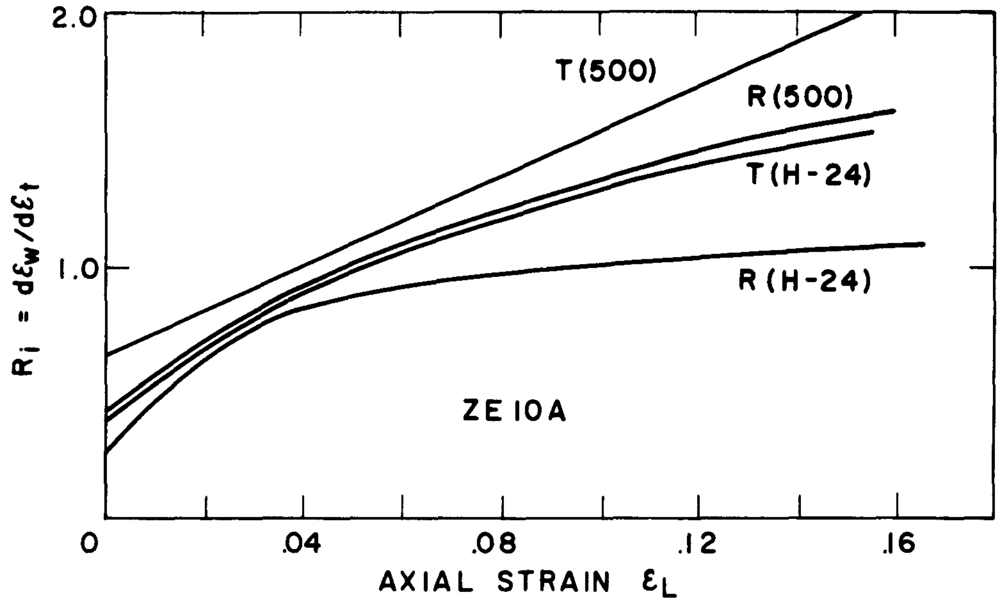

Figure 3. Variation of instantaneous strain ratio $R_i = d\epsilon_w/d\epsilon_t$ with tensile strains, ϵ_L, for magnesium alloy ZE10A in the H-24 condition and after a 3-hour anneal at 500°F. R and T indicate rolling and transverse direction tests respectively.

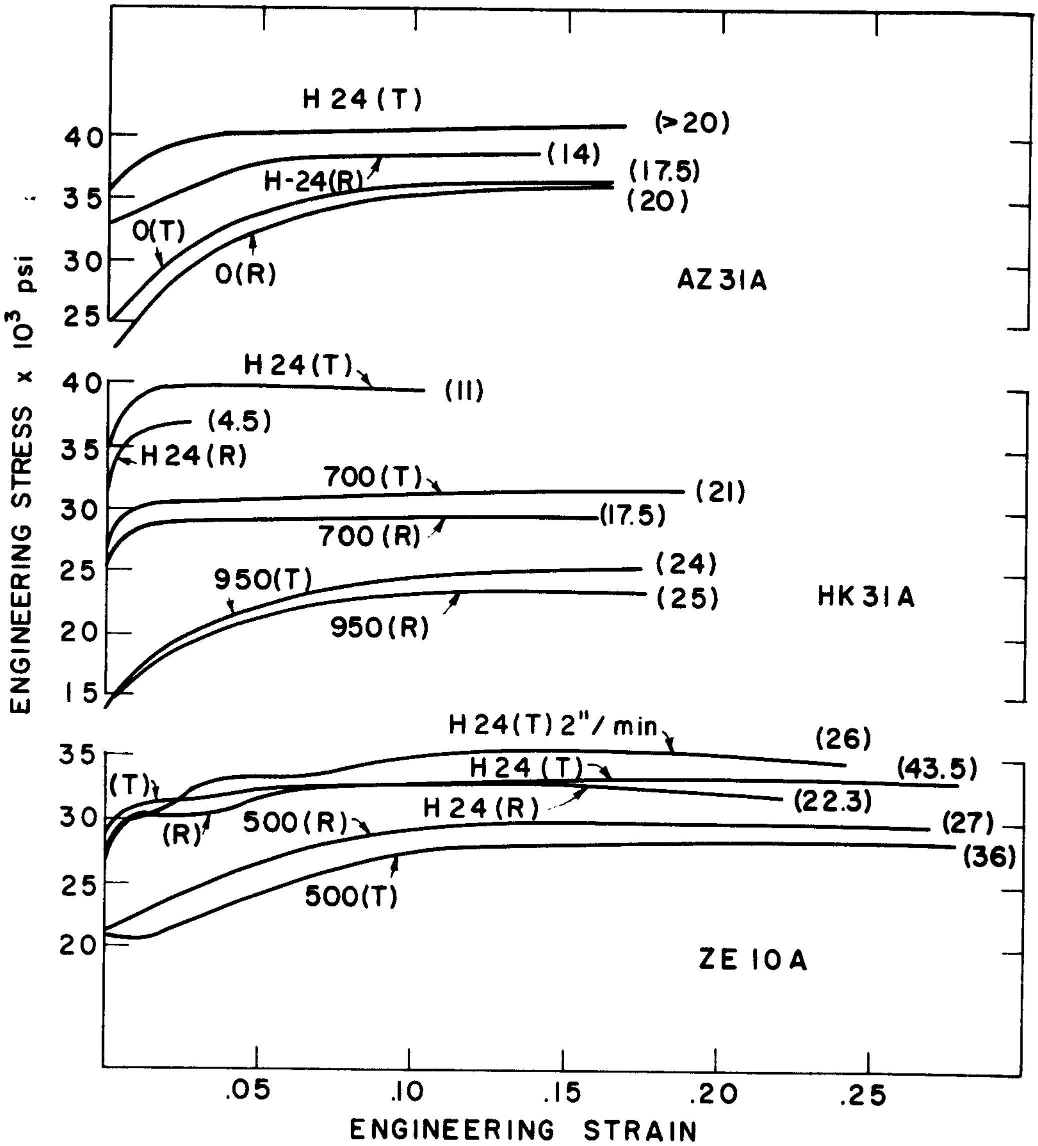

Figure 4. Engineering stress-strain curves for AZ31B in the H-24 and 0 conditions, HK31A in the H-24 condition and after anneals of one hour at 700°F and 950°F, and ZE10A in the H-24 condition and after an anneal of 3 hours at 500°F. R and T indicate rolling and transverse direction tests. The percent elongation at fracture is indicated at the end of each curve. All tests were at 0.02"/minute drive rate except one ZE10A-H24 transverse test for which the rate was 2"/minute.

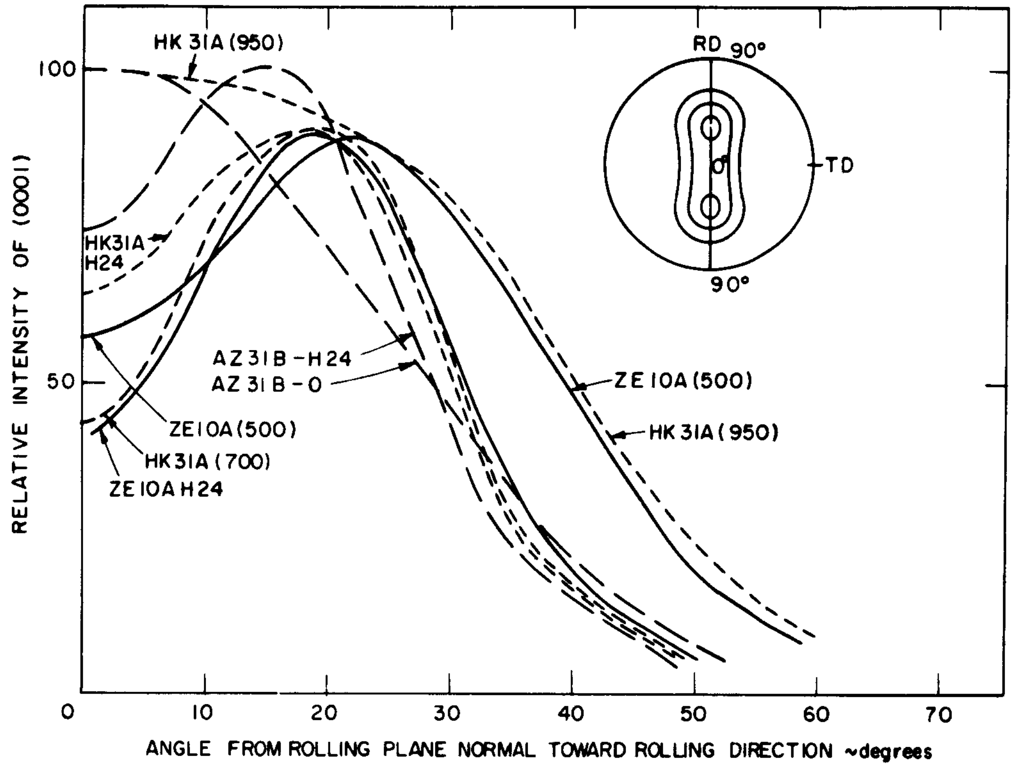

Figure 5. Profiles of (0001) pole figures for the magnesium alloy sheets showing the rolling direction spread of the intensity of (0001) reflections. The curves are the average of the intensities along great circles from the rolling plane normal to both the positive and reverse rolling directions as indicated at upper right.

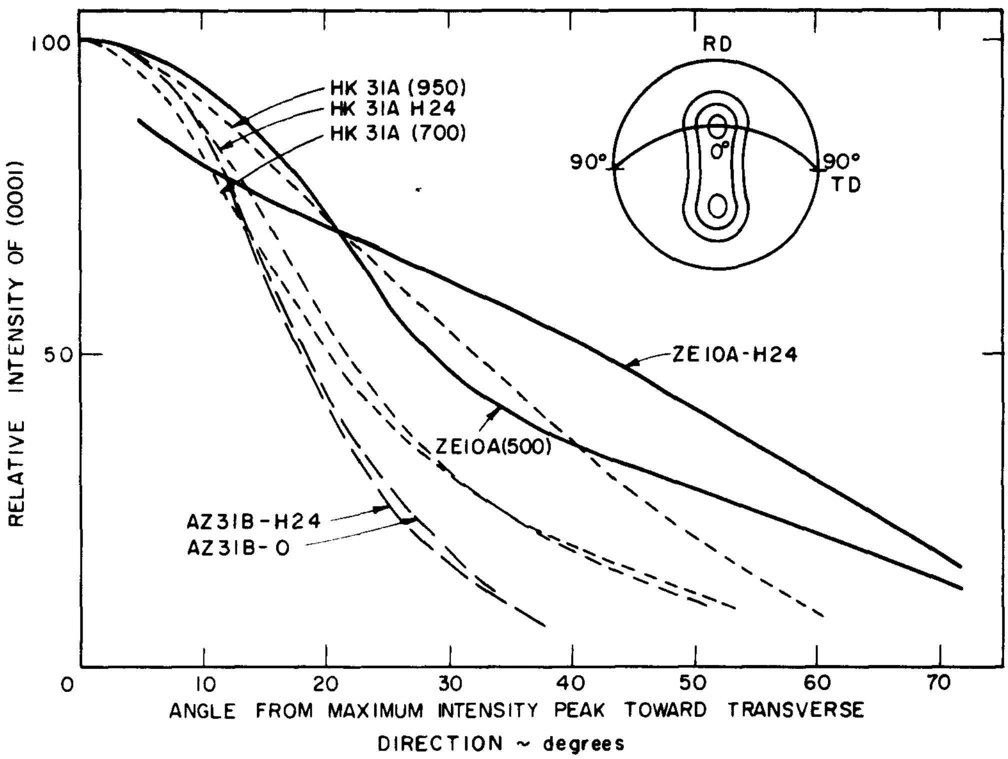

Figure 6. Profiles of the (0001) pole figures for the magnesium alloy sheets showing the transverse direction spread of the intensity of (0001) reflections. The curves are the pole figure profiles along great circles containing the maximum intensity peaks and the transverse directions as indicated at upper right.

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